Power Consumption in Agitated Tanks with Obliquely Corrugated Wall

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The power consumption of the agitated tanks which are innovative in that their shell walls are corrugated in an oblique configuration, has been measured in liquid single phase system and gas-liquid two phase system. The experimental results have been correlated by the equation considering the fluid drag at the corrugated wall in single turbulent systems, and by Michael-Miller's equation in gas-liquid two phase systems.

1. Introduction

Mechanical agitation of various fluids and mixtures has been extensively utilized in a variety of industrial processes to promote homogenization, chemical reactions, heat and mass transfer, and so on.

For these purposes, many different kinds of agitated tanks and impellers have been developed and commercialized. For example, radial flow impellers such as paddles and flat blade turbines are used for agitating gas-liquid systems and axial flow impellers such as propellers and pitched blade turbines are used for suspending solids particles in solids-liquid systems. Conventional tanks have been usually equipped with baffled plates at their walls to prevent voltex flow from taking place at pure liquid free surfaces at the expense of the agitating power, which is several times larger than that of non-baffled tanks. Some of agitated tanks have a conical bottom[5] or are equipped with the 45°-cone plate below the impeller to promote the circulating flows[7].

In the present study, the tanks which are innovative in that their shell walls are corrugated in an oblique configuration, have been used. These tanks can control the vortex flow at the expense of less agitating power than that in conventional baffled tanks, and have the advantage that they can be easily cleaned up throughout.

The blending performance, gas-liquid and solids-liquid mass transfer characteristics of these tanks have been evaluated and it has been shown that these tanks are more useful as mixing and mass transfer equipments than conventional agitated tanks[2].

The power consumption which is an important factor in evaluating gas-liquid and solids-liquid mass transfer characteristics, have been measured in liquid single phase and gas-liquid two phase systems and correlated in terms of modified Newton number in fully developed turbulent region.

2. Experimental

The power consumption in the tanks with obliquely corrugated wall has been measured by using a torque meter (SHINKOH TM/0.5B, 5B, 10B). The schematic

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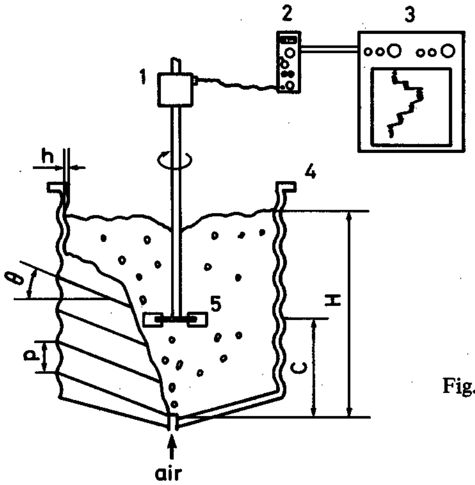

Fig. 1 Schematic diagram of experimental apparatus:
1 torquemeter; 2 amplifier; 3 recorder; 4 obliquely-corrugated tank; 5 impeller

diagram of experimental apparatus is shown in Fig. 1.

The diameter of the tanks was kept constant at 40 cm. The angle of oblique corrugation, θ, was varied from 15° to 90°. The depth of corrugation, h, was set at 0.3, 0.7 and 1.0 cm. The pitch, p, was set at 6.8 cm.

The liquid viscosity was varied from 0.001 Pa.s to 1.0 Pa.s by using water and sucrose solutions. The power consumption of the tanks for a gas-liquid system has also been measured. In order to compare the power consumption of these tanks with that of conventional tanks, the cylindrical tank without baffles (40cm diameter) was employed. Four turbine impellers of 7 to 24 cm diameters were used.

3. Results and Discussion

3.1 Liquid single phase

Figures 2, 3, and 4 show the power correlation in the obliquely corrugated tanks with a liquid single phase using 6-blade flat disk turbines of 15, 18 and 24 cm diameters, respectively. In these figures, Newton number defined by Eq. (1) is correlated with Reynolds number defined by Eq. (2).

$$Ne = \frac{P}{\rho n^3 d^5} \tag{1}$$

$$Re = \frac{d^2 n \rho}{\mu} \tag{2}$$

The power correlation for conventional tanks of Rushton et al.[6] obtained at C/H = 1/3 is also plotted in Fig. 2 for comparison. The present experimental results obtained at C/H = 1/2 can be compared with their correlation because the power consumption is not dependent of the impeller clearance, C/H, from tank bottom as shown in Fig. 5.

It can be seen from these figures that, although the variation of Newton number with Reynolds number for these tanks is similar to that for the tank without baffles, Newton number becomes dependent also on the oblique angle above a certain Reynolds

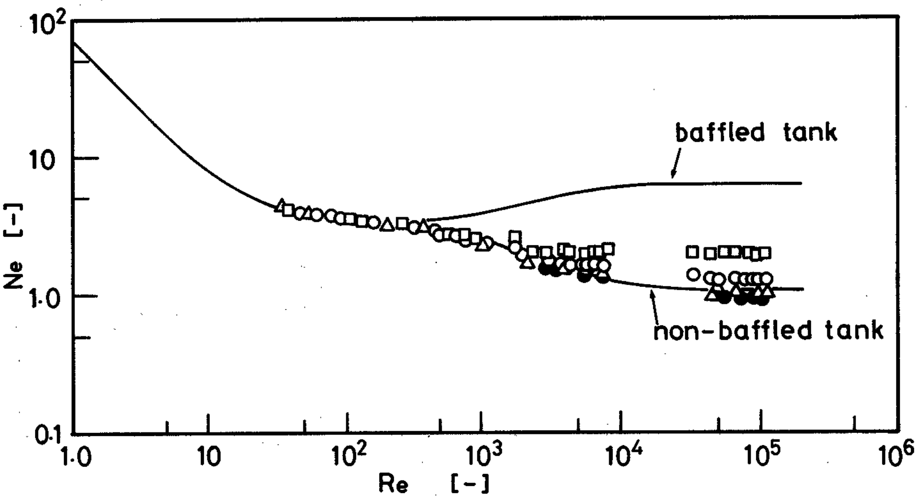

Fig. 2 Power correlation of obliquely corrugated tanks with liquid single phase: turbine impeller of 15 cm diameter
□ θ = 90° ; ○ θ = 50° ; △ θ = 30° ; ● non-baffled tank
— Rushton et al.[6)]

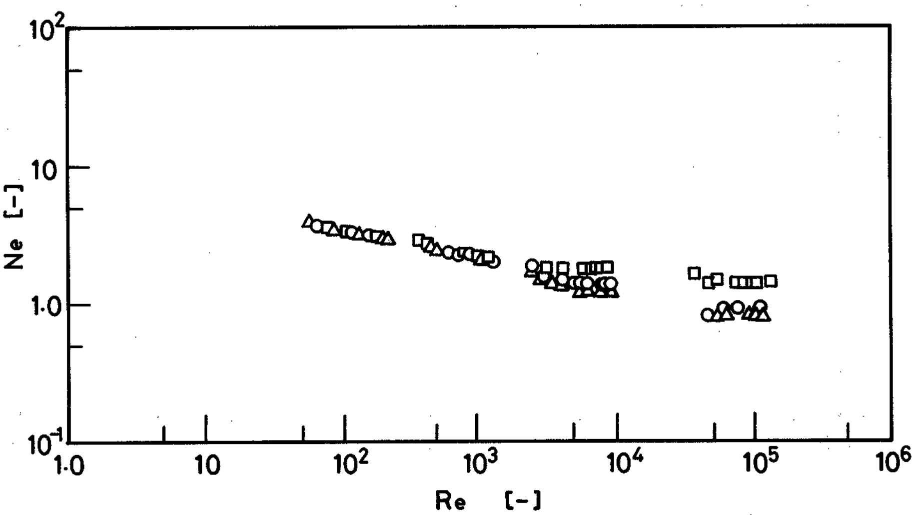

Fig. 3 Power correlation of obliquely corrugated tanks with liquid single phase: turbine impeller of 18 cm diameter
□ θ = 90° ; ○ θ = 50° ; △ θ = 30°

number, which depends on the impeller diameter.

Newton number, $Ne,_t$, in fully developed turbulent region ($Re > 5 \times 10^4$) is plotted against the dimension of impeller for the wall with various angles and depths of corrugation in Fig. 6. As can be seen, $Ne,_t$ increases as the angle and depth of corrugation become larger. This is due to an additional drag force at the tank wall by the corrugation.

Generally speaking, the torque applied to the impeller shaft is equal to the sum of all the moments exerted by the tangential shear stress at the inner wall surfaces of the agitated tank[3)]. Therefore, it has been assumed that the power dissipation, P, in the

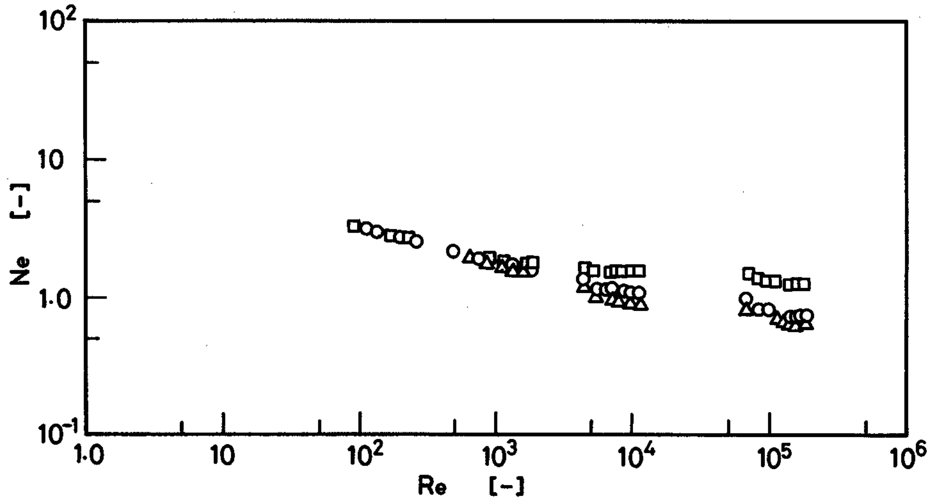

Fig. 4 Power correlation of obliquely corrugated tanks with liquid single phase: turbine impeller of 24 cm diameter
□ $\theta = 90°$; ○ $\theta = 50°$; △ $\theta = 30°$

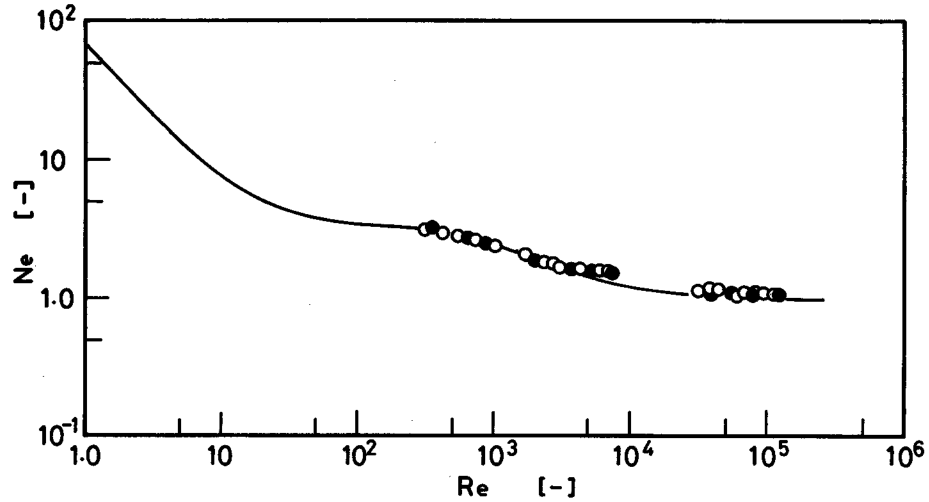

Fig. 5 Power correlation of 50°-obliquely corrugated tank with liquid single phase for different impeller clearance:
○ C = H/2; ● C = H/3
— Rushton et al.[6)]

obliquely corrugated tanks consists of the power dissipation, P_{non} in non-baffled conventional tanks and the additional dissipation, ΔP at the corrugated wall:

$$P = P_{non} + \Delta P \tag{3}$$

ΔP can be evaluated by Eq. (4):

$$\Delta P = \frac{1}{2} C_d \cdot \rho \ A \cdot v_\theta^3 \tag{4}$$

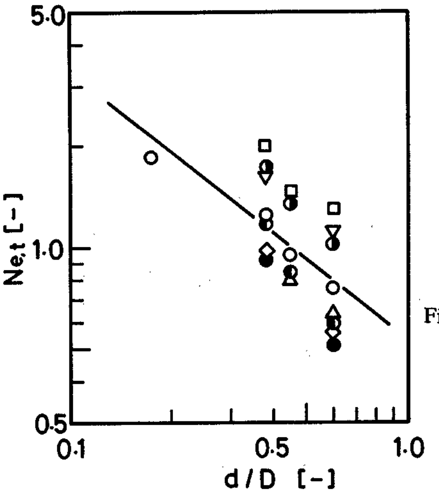

Fig. 6 Newton number in fully developed turbulent flow region: ◇ $\theta = 15°$; △ $\theta = 30°$; ○ $\theta = 50°$; ▽ $\theta = 75°$; □ $\theta = 90°$ (for d = 15 cm and h = 7 mm) ◐ $\theta = 50°$ and h = 3 mm ; ◑ $\theta = 50°$ and h = 10 mm ; ● non-baffled tank

The value of C_d is assumed to be equal to that for a cylinder with the axis vertical to the flow direction in turbulent fluid[1]. v_θ is the tangential velocity of fluid at the tank wall for the cylindrical tank without baffles and have been given experimentally as[3]

$$v_\theta = \frac{r_c\, 2n\pi}{D/2} \cdot \left(\frac{D/2}{r_c}\right)^{\beta} \qquad (\beta: 0-0.4) \qquad (5)$$

The radius of cylindrically rotating voltex at a central portion, r_c[3], can be calculated in fully developed turbulent flow region by Eq. (6):

$$\lim_{Re\to\infty} (r_c) = \lim_{Re\to\infty} \left(\frac{d}{2} \cdot \frac{Re}{10^3 + 1.43Re}\right) = \frac{d}{2.86} \qquad (6)$$

The projected area, A, is a function of the depth, h, angle, θ and number, n_p, of corrugation and liquid depth, H and is given by Eq. (7):

$$A = n_p \cdot h \cdot H \cdot \sin\theta \qquad (7)$$

Combining Eqs. (3), (4), (5) with $\beta = 0.2$[8], (6) and (7), we obtain Eq. (8):

$$Ne_{,t} = \frac{P}{\rho n^3 d^5} = Ne_{,non} + 2.92\, h \cdot H \cdot \sin\theta \cdot (d/D)^{2.4}\, n_p / d^2 \qquad (8)$$

where $Ne_{,non}$ is Newton number for the cylindrical tank without baffles, defined by $Ne_{,non} = P_{non}/\rho n^3 d^5$. The experimental values of $Ne_{,t}$ are compared with the values calculated by Eq. (8) in Fig. 7. The experimental results are in good agreement with the calculated values.

3.2 Gas-liquid two phase system

Gas dispersion reduces the power requirement for agitation of gas-liquid two phase

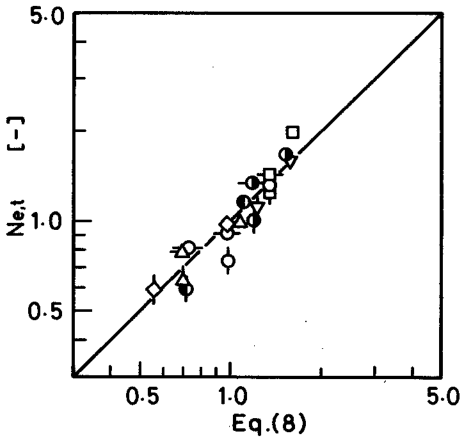

Fig. 7 Correlation of Newton Number in fully developed turbulent flow region by Eq. (8):
◇ $\theta = 15°$; △ $\theta = 30°$; ○ $\theta = 50°$;
▽ $\theta = 75°$; □ $\theta = 90°$
(for $d = 15$ cm and $h = 7$ mm)
◐ $\theta = 50°$ and $h = 3$ mm ; ◑ $\theta = 50°$ and $h = 10$ mm
-- for $d = 18$ cm; ¦ for $d = 24$ cm

systems and many attempts have been made to correlate this reduction with the fluid properties and the system geometry. Among these, the correlation by Michael and Miller[4] has been widely used and is also utilized in the present study:

$$P_g = a(P^2nd^3/Q^{0.56})^\gamma \tag{9}$$

Where Q is the gas flow rate, P is the power consumption for a liquid single phase calculated from Eq. (8), the coefficient a and the exponent γ are dependent on the system geometry. For the standard 6-blade flat disk turbine (d/D = 1/3) under the fully baffled condition, a = 0.706 and γ = 0.45[4]. Figure 8 shows the power consumption, P_g, of the obliquely corrugated tanks with gassed liquids plotted according to Eq. (9). As can be seen from this figure, the power consumption, P_g, is well correlated by Michael and Miller's relation even though the tanks of different oblique angle or different depth of corrugation and the impellers of different sizes are used. The value of

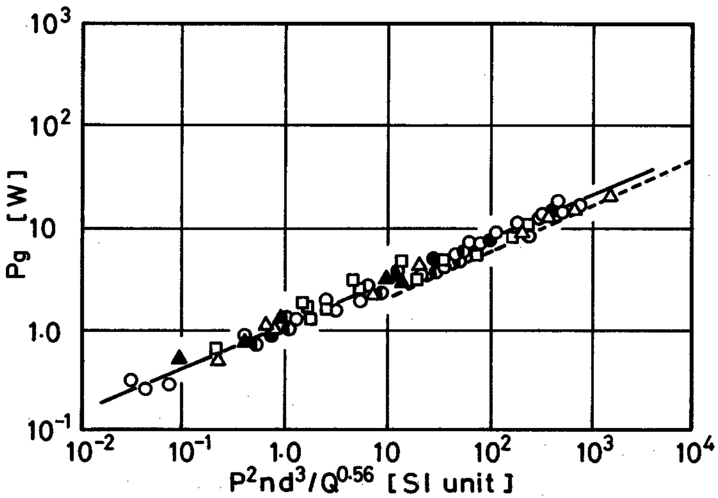

Fig. 8 Power consumption for gas-liquid two phase system: turbine impeller of 15 cm diameter
□ $\theta = 30°$; ○ $\theta = 50°$; △ $\theta = 90°$ for $h = 7$ mm
◐ $\theta = 50°$ for $h = 3$ mm ; ● $\theta = 50°$ for $h = 10$ mm ; ▲ non-baffled tank
— Michael and Miller ($a = 0.706$, $\gamma = 0.45$)[4]

a and γ in Eq. (9) for the obliquely corrugated tanks is 1.10 and 0.43, respectively.

4. Conclusion

The power consumption in the agitated tanks with obliquely corrugated wall using 6-blade flat disk turbines has been measured in liquid single phase and gas-liquid two phase system. For liquid single phase system, the power consumption has been well correlated in terms of modified Newton number, which takes the fluid drag at the corrugated wall into account, and for gas-liquid systems, the power consumption has been well described by Michael and Miller's correlation.

Nomenclature

a	:	coefficient in Eq. (9)
A	:	projected area, m^2
C	:	impeller clearance from tank bottom, m
C_d	:	fluid drag coefficient, –
d	:	impeller diameter, m
D	:	tank diameter, m
h	:	depth of corrugation, m
H	:	liquid depth, m
Ne	:	Newton number, –
$Ne_{,t}$	:	modified Newton number in fully developed turbulent flow region, –
$Ne_{,non}$	:	Newton number in cylindrical tank without baffles, –
n	:	rotating speed of impeller, 1/S
n_p	:	number of corrugation, –
p	:	pitch of corrugation, m
P	:	power consumption, W
P_g	:	power consumption in gas-liquid system, W
P_{non}	:	power consumption in cylindrical tank without baffles, W
ΔP	:	energy dissipated per unit time at corrugated wall, W
Q	:	gas flow rate, m^3/S
r_c	:	radius of cylindrical rotating voltex, m
Re	:	Reynolds number, –
v_θ	:	tangential velocity of fluid at the tank wall, m/s
β	:	exponent in Eq. (5)
γ	:	exponent in Eq. (9)
θ	:	angle of obliquely corrugation, degree
μ	:	liquid viscosity, *Pa.s*
ρ	:	liquid density, kg/m^3

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